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# VERTICAL LASER BEAM PROPAGATION THROUGH THE TROPOSPHERE

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THROUGH THE TROPOSPHERE

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## PURPOSE

The development of larger and more sophisticated satellites has led to an expanding need for increased data transmission capabilities to transfer the information obtained by these satellites to earth based data receiving facilities. Estimates of NASA's future needs indicate that telemetry channels with a capacity of 300 megabits per second will be required on advanced earth observation satellites. Due to the high cost of the network of tracking stations which would be required to keep a low orbiting satellite in view, the data will first be transferred to one of several synchronously orbiting data relay satellites which can be constantly seen by a few ground data receiver terminals. Because of their short wavelength compared to microwaves, laser communications systems offer a great improvement in size, weight, and power consumption over microwaves, and, therefore, NASA is actively developing laser communications for space to space and space to ground data transfer.

As part of this effort, the characteristics of the earth's atmosphere and its effects upon laser beams has been investigated in a series of balloon borne, optical propagation experiments. These experiments have been designed to simulate the space to ground laser link. In this paper, an experiment to determine the amplitude fluctuation, commonly called scintillation, caused by the atmosphere will be described.

## OBJECTIVES

The objective of the experiment was to simulate a space to earth laser data transmission link by directing a balloon borne laser transmitter from an altitude well above all significant turbulence to an instrumented ground receiving station.

Specific objectives were as follows,

1. Measure the statistics of scintillation as a function of receiver aperture.
2. Compare the statistics of the laser scintillation to available data on stellar scintillation.
3. Compare the statistics of daytime scintillation with existing data on nighttime scintillation.

## THEORY AND ANALYSIS

Consider Figure 1 which shows a spherical wave source at altitude H above the earth's atmosphere, and a receiver of diameter D pointed at the source. Between source and receiver is an arbitrary distribution of turbulence which we will assume is isotropic when measured in any plane parallel to the earth, but which will vary in some fashion as a function of altitude. Characterizing the strength of scintillation for a small aperture by the normalized standard deviation of irradiance, and the strength of turbulence by the refractive-index-structure constant the scintillation may be calculated for the case of weak scintillation by the following expression,

$$\frac{\sigma_I}{\bar{I}} = 2 [C_\ell(0)]^{1/2} = 2 \left[ 0.56 k^{7/6} \sec^{11/6} \theta \int_0^H dh C_N^2(h) (h\mu)^{5/6} \right]^{1/2}$$

where

$C_\ell(0)$  = log-amplitude variance

$k$  = wave number =  $2\pi/\lambda$

$\theta$  = zenith angle

$C_N^2(h)$  = refractive-index-structure constant at altitude h

$\mu$  =  $1 - h/H$

We immediately see that for small apertures the scintillation is aperture independent, but has a pronounced dependence upon wavelength, zenith angle and the vertical distribution of turbulence. The factor is  $\mu$  used to account for the spherical wave nature of the source. By using the artifice of allowing the source to recede to infinity, the source can be made to approximate an infinite plane wave, and the factor  $\mu$  becomes unity leaving us with the standard plane wave equation for scintillation.

As the aperture is increased, the magnitude of the normalized signal standard deviation will decrease below the normalized irradiance standard deviation due to the averaging effect of the receiver aperture upon the random optical distribution of irradiance in the receiver plane. This effect is usually accounted for by a term known as an aperture averaging factor which relates the two normalized standard deviations.

$$\frac{\sigma_S}{\bar{S}} = \Theta^{1/2} \frac{\sigma_I}{\bar{I}}$$

In the limiting case for very large apertures, Fried<sup>2</sup> has derived an expression for the aperture averaging factor under conditions of weak scintillation

$$\Theta = \frac{4.313 D^{-7/3} \sec^3 \theta}{C_\ell(0)} \int_0^H dh C_N^2(h) h^2 \mu^{-1/3}$$

Combining the expressions for normalized standard deviation of irradiance and aperture averaging factor, we obtain the scintillation for large apertures

$$\frac{\sigma_S}{\bar{S}} = 4.15 D^{-7/6} \sec^{3/2} \theta \left[ \int_0^H dh C_N^2(h) h^2 \mu^{-1/3} \right]^{1/2}$$

We immediately see that for large aperture there is, a distinct aperture dependence, a new zenith angle and turbulence profile dependence, but no wavelength dependence. In the range of aperture sizes between very large and very small, there is no theoretical derivation for the aperture dependence, and therefore, experimental data must be used to fabricate an empirical equation for the aperture averaging factor. While there is no data on laser propagation from space to earth, there is an extensive amount of aperture dependence data which has been obtained from stellar scintillation studies. We have plotted this data in Figure 2 and fitted an empirical equation for the aperture averaging factor suggested by Fried<sup>8</sup>.

$$\Theta = \left[ 1 + \left( \frac{D}{d_0} \right)^{7/6} + \left( \frac{D}{d_0} \right)^{7/3} \right]^{-1}$$

where  $d_0$  is

$$d_0 = 2.399 k^{-1/2} \text{ sec}^{1/2} \theta \left\{ \frac{\int_0^\infty dh C_N^2(h) h^2 \mu^{-1/3}}{\int_0^\infty dh C_N^2(h) (h\mu)^{5/6}} \right\}^{3/7}$$

The above aperture averaging factor has the virtues of fitting the equations for the limiting values as well as the experimental values for intermediate apertures. It represents our best estimate of aperture averaging.

## METHOD

In order to simulate a space to earth laser propagation link, a helium-neon laser transmitter was installed in a gimballed platform aboard the gondola of a high altitude research balloon. The balloon was launched and flown by the Air

Force Cambridge Research Laboratories Balloon Detachment at White Sands Missile Range, and tracked by an optical theodolite of 76 cm aperture. An argon laser beacon directed at the balloon from the theodolite allowed a star tracker mounted on the gimballed platform to direct the helium-neon laser beam at the theodolite optics. A variable aperture stop system allowed the effective collecting diameter of the theodolite to be changed in steps of two from 8 cm to 64 cm with an additional stop used for the full 76 cm aperture. The signal received was detected by a photomultiplier and recorded for later processing. Significant system parameters are shown in Figure 3.

## RESULTS

The flight profile is shown in Figure 4, data presented in this paper came from the third interval of laser operation between 1200 and 1300 Mountain Standard Time on October 19, 1973. A device known as a thermosonde<sup>9</sup> was used to measure the vertical profile of turbulence shortly before the experiment. Results are shown in Figure 5 together with standard Rawinsonde plots of the vertical profiles of temperature and wind speed. Using this data, we obtain a value of  $d_0$  of

$$d_0 = 0.137 \text{ sec}^{1/2} \theta$$

for the wavelength  $0.63 \times 10^{-6}$  meters.

The next graph illustrates the major results of the experiment (Figure 6). In this plot, the ordinate is the normalized standard deviation of received signal on a logarithmic scale and the abscissa is the receiver diameter in meters also on a logarithmic scale. Data points are represented by the small circles and

each represents a value taken from a one minute sample of scintillation. The variation in observed values is due to the non-stationarity of the atmospheric turbulence rather than experimental difficulties, and is of approximately the same magnitude as seen for stellar scintillation. A curve of the same shape as that for stellar scintillation, but with the magnitude adjusted for best fit has been drawn through the data. The corresponding asymptotic limits for very small and very large apertures are shown by the dashed lines. The previous stellar scintillation curve is shown for reference and demonstrates that the laser scintillation was approximately 46% higher than average stellar scintillation. This slight increase does not necessarily indicate any systematic difference between stellar and laser scintillation as the limits of the day to day variation in stellar scintillation easily include all of the observed laser data. All data has been corrected to a zenith angle of  $45^\circ$ . The normalized power spectral density of the scintillation is a function of aperture with large apertures acting as low pass filter to remove the high frequencies. Figure 7 shows the spectral density for the largest and smallest apertures used in the experiment. Results are similar to stellar scintillation spectra.

## CONCLUSION

The major conclusions we can draw from the experiment are that the scintillation of a space to ground laser link is similar to that of stellar scintillation, and that there are only minor differences between day and night. We have found nothing to indicate that the statistics of laser scintillations are in anyway different from those of an incoherent stellar source. However due to the limited amount of data, further work needs to be done in this area.

## ACKNOWLEDGMENTS

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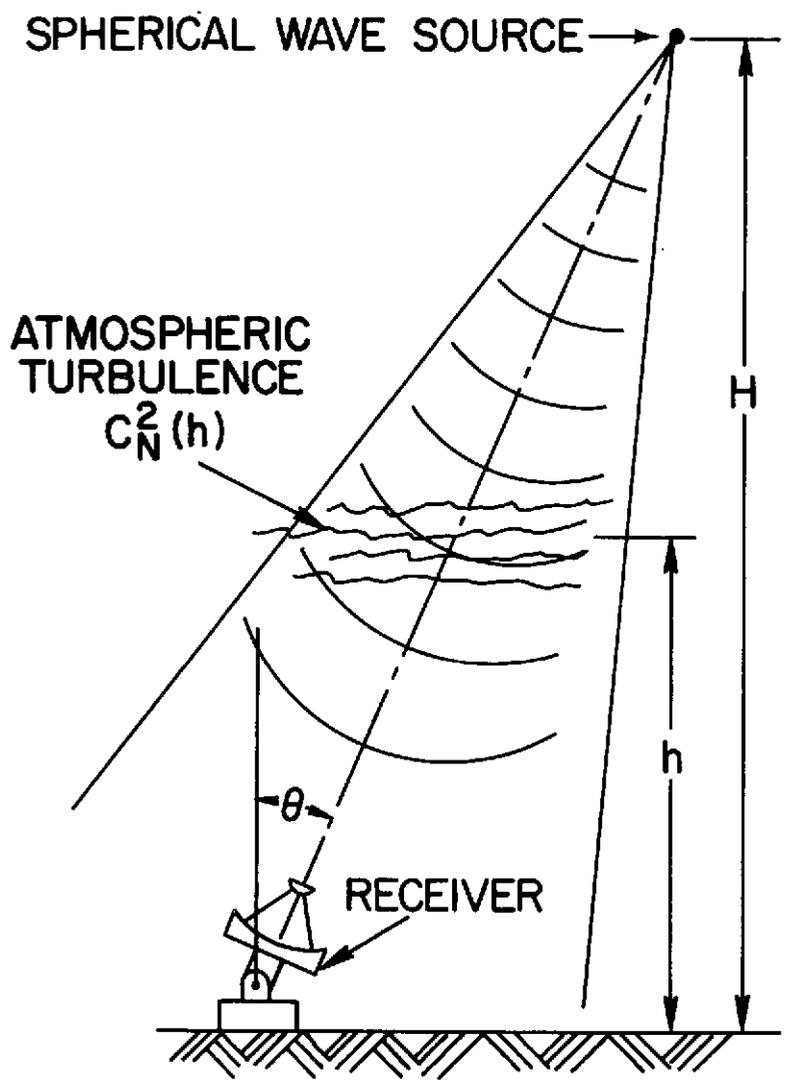


Figure 1. Propagation Path

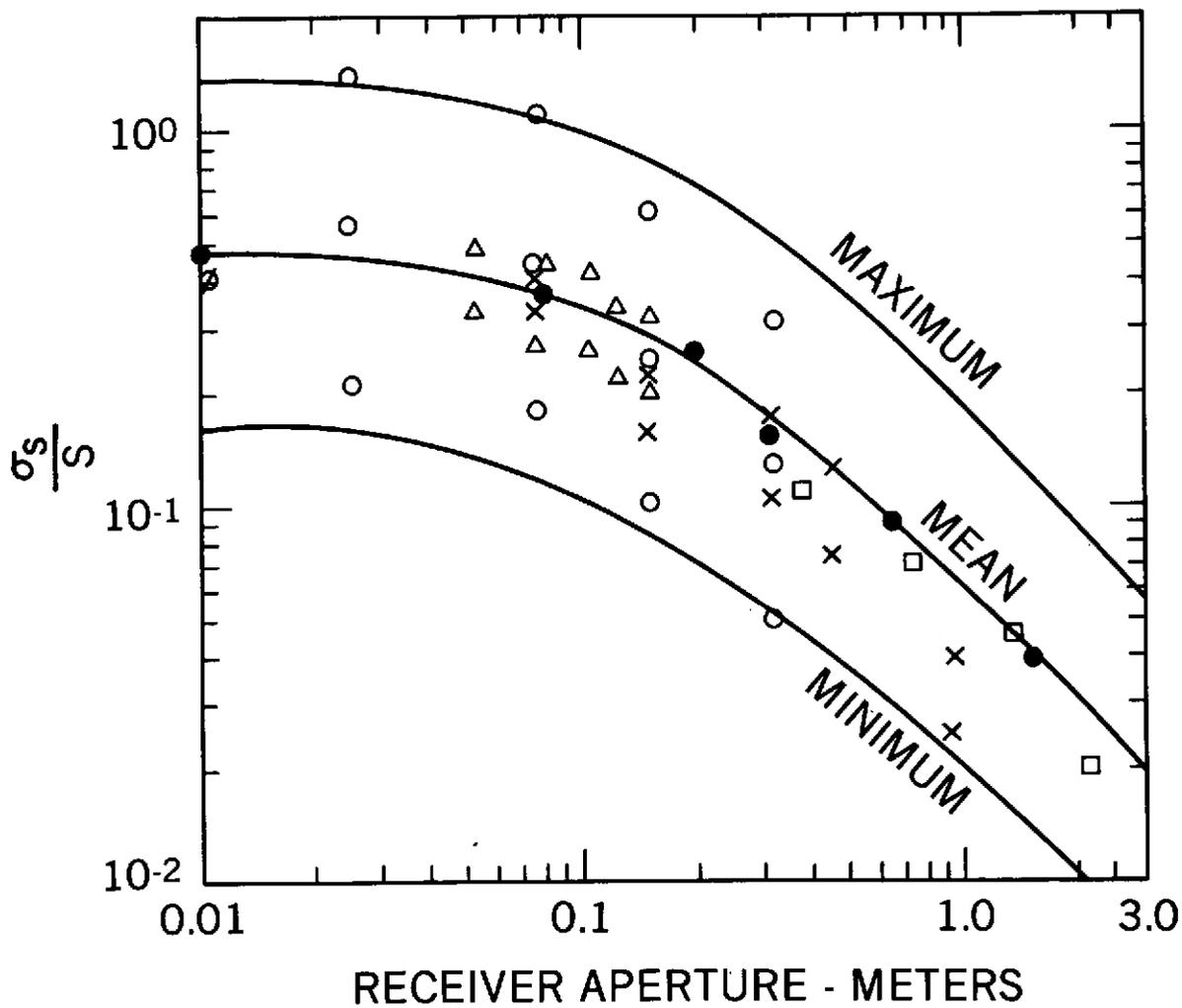


Figure 2. Stellar Scintillation

## SOURCE

HEIGHT	26.8	KILOMETERS
RANGE	42.5 - 92.9	KILOMETERS
ZENITH ANGLES	53 - 74	DEGREES
BEAM DIVERGENCE	20	MILLIRADIANS
POINTING ERROR	0.50	MILLIRADIANS (rms)
WAVELENGTH	0.63	MICROMETERS
POWER	1.5	MILLIWATTS

## RECEIVER

APERTURES	8, 16, 32, 64, 76	CENTIMETERS
OBSCURATION	20 (ON 64 AND 76)	CENTIMETERS
RECEIVER FIELD	2	MILLIRADIANS
POINTING ERROR	0.5	MILLIRADIANS (PEAK)

Figure 3. System Parameters

# ZA AND ALT. VS. TIME (MST) FOR FLIGHT NO. 5

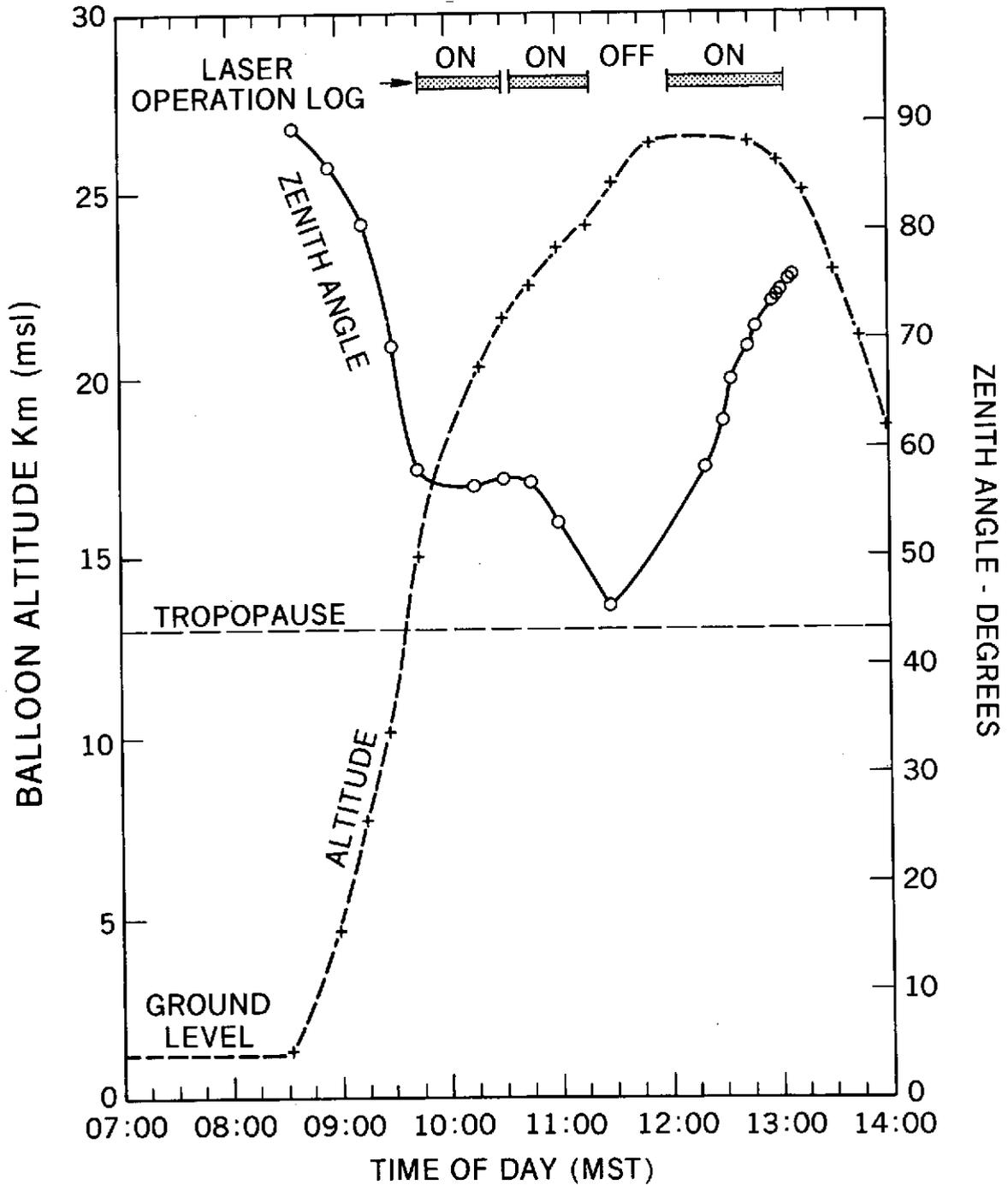


Figure 4. Flight Profile

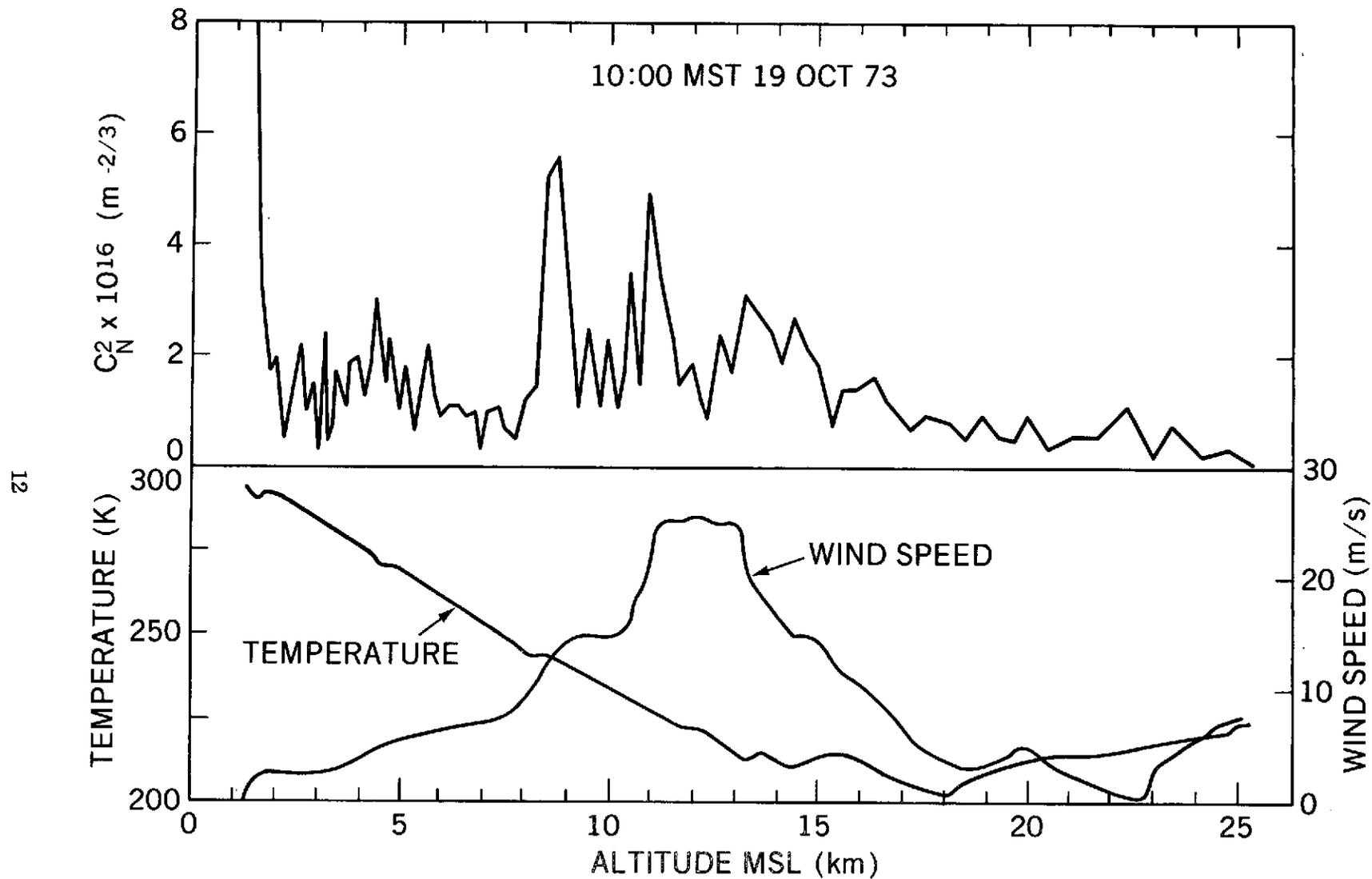


Figure 5. Turbulence Profile

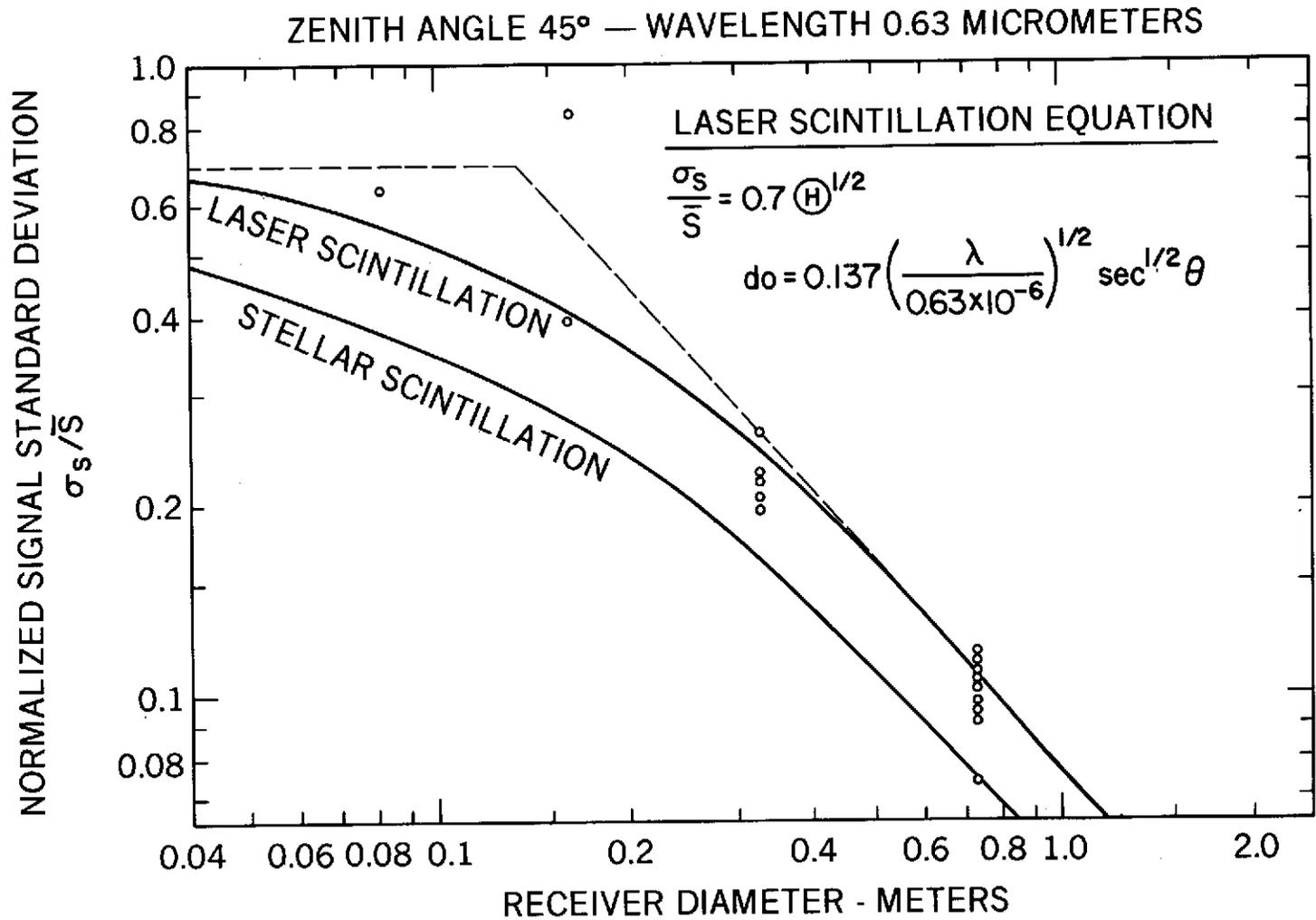


Figure 6. Scintillation vs. Aperture

He Ne SCINTILLATION  
10:20 MST 19 OCT 73

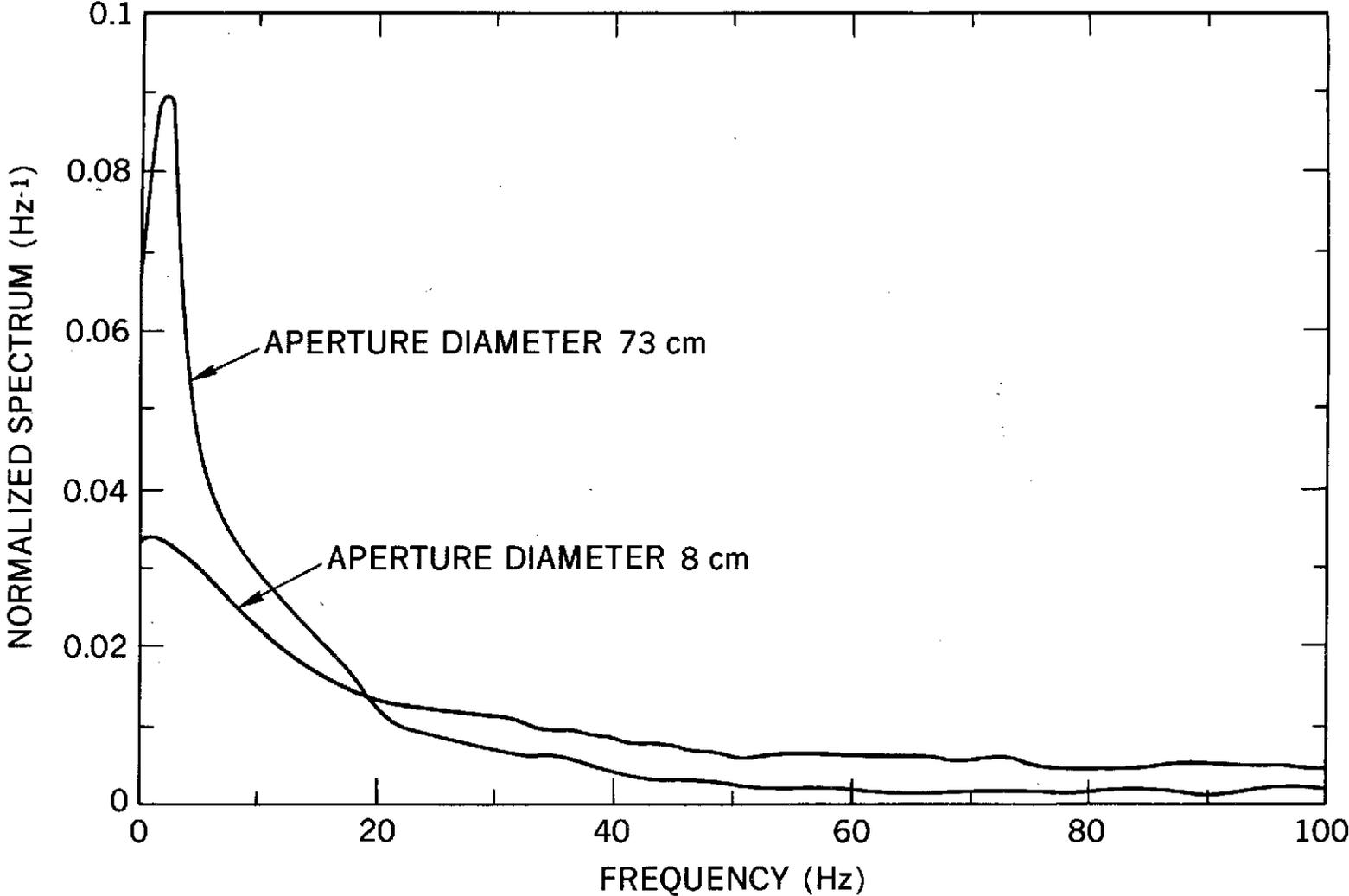


Figure 7. Power Spectral Density